Totally Chaotic Poissonian-Like Sources in Multiparticle Production Processes?

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Abstract

In all multiparticle processes the concept of sources directly emitting finally observed secondaries (mostly pions) plays crucial role. Here we shall present them from yet another point of view in which elementary sources composing all processes (from e^+e^- annihilation, via pp up to AA interactions) remain both totally 'chaotic' and Poissonian at the same time.

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1 Introduction

For time being the multiparticle production processes can be described only in a phenomenological way. As a rule they are visualised as proceeding in two steps: first a number of more or less defined intermediate objects (we shall called them *sources*) is formed and next follows their hadronization. Sources are heavy, nonresonant and unstable objects and models differ in their definition and in details of their hadronization [1, 2].

The notion of sources is essential in explaining such general features of multiparticle production processes as the broadening of the multiplicity distributions $P(n)$ when the complexity of the colliding objects increases, cf. Fig. 1, and that the second factorial cumulant is almost constant (it decreases only insignificantly, cf. Fig. 2).

There is another possible characteristic of the source discussed recently [6]. It is represented by parameter λ defined as

$$\lambda = [C_2(p_1, p_2) - 1]_{\lim|p_1 - p_2| \to 0}\,, \tag{1}$$

where $C_2(p_1, p_2)$ is the Bose-Einstein correlation (BEC) term of two identical bosons with momenta p_1 and p_2 [7]. This parameter was introduced as a measure of *correlation strength* in the simplest possible one-dimensional parametrization of C_2 in order to reduce systematic errrors when fitting the experimental results with theoretical curves (cf., for example, [8]). It has got very quickly quantum-optical interpretation as the *chaoticity parameter* [9, 10] and is widely accepted under this name in majority of phenomenological approaches to BEC. In this interpretation $\lambda = 1$ signals to-

tally chaotic (usually understood as thermal) emission of secondaries whereas $\lambda = 0$ means that they are radiated in a laser-like fashion. In other words, one expects that quantum-mechanical phases in different space-time points of the hadronization region are totally uncorrelated in the former case and fixed by one value in the later one [10, 6].

It was known from the very beginning that such interpretation of λ has its severe limitations and that it is also affected by the type of the parametrization of BEC used [11, 12, 8]. Especially emabarasing in this respect, although not much pursued (cf. [6]), are observations that:

- in in e^+e^- annihilation processes λ is nearly maximal [13] and practically λ does not depend on the multiplicity of produced secondaries;
- in the more complex NN collisions λ drops considerably and decreases with increasing multiplicity [14];
- this trend seems to continue when proceeding to hA collisions where $\lambda_{hA} < \lambda_{hh}$ is apparently observed [17] and in AA collisions where λ decreases with the atomic masses A [18].

2 Totally chaotic elementary emitting cels in the simplest e^+e^- collisions

Taken naively these observations could indicate an increase of *coherence* from e^+e^- to AA collisions, an impossible conclusion from the point of view of the observed in Fig. 1 behaviour of $P(n)$. In [6] a discussion of λ trying to reconcile experimental

observations presented above was given with elementary source being totally *coherent*. We shall demonstrate now that one can obtain equally good description of data with *totally chaotic* elementary emitting cells *EEC* and observed changes of parameter λ (defined in eq.(1)) being caused by the increasing complexity of reaction - increasing and fluctuating number of such cells.

Our *elementary emitting cell* (*EEC*) is assumed to produce bosons (mainly pions) in only one momentum state $|p\rangle$. Therefore, due to the Bose-Einstein statistics, the multiplicity distribution of pions from such source is purely of geometric (Bose-Einstein) type corresponding to the *chaotic* field limit

$$P(n) = \frac{1}{1+\langle n\rangle}\left(\frac{\langle n\rangle}{1+\langle n\rangle}\right)^n \tag{2}$$

and, correspondingly, for a single *EEC* one has $\lambda = 1$ (i.e., all particles are fully correlated in the sense that presence of any one of them stimulates additional emission of other secondaries which is limited only by the energy-momentum conservation constrains not considered here). On the contrary, particles originating from different *EEC*'s are totally uncorrelated (again, in the above mentioned sense), therefore for them $\lambda = 0$. Notice that our *EEC*'s are more fundamental than sources mentioned at the beginning (fireballs, clusters, strings etc). Actually these sources, which we shall denote $\mathbf{S}$ in what follows, contain always a whole spectrum of *EEC*'s corresponding to the distribution of momenta of the produced particles ($\sim \exp(-p/p_0)$). We shall assume here that in multiparticle production processes all *EES*'s are produced independently. In the case when we have n originating from k *EEC*'s we are immediately lead to the famous negative binomial (NB) distribution [2, 19]

$$P(n;k) \quad = \quad \sum_{n_1,n_2,\dots,n_k} \prod_i \left[\frac{\left(\frac{\langle n\rangle}{k}\right)^{n_i}}{\left(1+\frac{\langle n\rangle}{k}\right)^{n_i+1}}\right]$$

$$= \binom{n+k-1}{n} \frac{\left(\frac{\langle n\rangle}{k}\right)^n}{\left(1+\frac{\langle n\rangle}{k}\right)^{n+k}} \qquad \stackrel{k\to\infty}{\longrightarrow} \qquad P(n) = \frac{\langle n\rangle^n}{n!}\mathrm{e}^{-\langle n\rangle} \tag{3}$$

which in the case of large number of EEC's (understood as $\langle n\rangle/k << 1$) leads to Poissonian distribution of produced secondaries n. For widely tested experimentally variance of multiplicity distribution it means that

$$D^2 = \langle n\rangle \left(1+\frac{\langle n\rangle}{k}\right) \qquad \stackrel{k\to\infty}{\longrightarrow} \qquad \langle n\rangle. \tag{4}$$

Therefore, it is quite natural in our picture that in the e^+e^- annihilation processes we shall indeed at the same time observe both $P(n)$ being poissonian(-like) and λ near 1.

3 More complex hadronic and nuclear collisions

When one proceeds to more complex hadronic collisions the first thing to recognize is that now the broad hadronic multiplicity distributions can arise in a natural way from any incoherent superposition of many narrow ('e^+e^--type like') sources **S** [20]. Suppose that we consider a fluctuating number C of such independent narrow (Poissonian) **S**'s with n_i particles in each and with total multiplicity $N = \sum_{i=1}^{C} n_i$ and mean $\langle N\rangle = \langle n\rangle\langle C\rangle$. As a result we have then a compound Poissonian distribution [21]

$$P(N) = \sum_{C=0}^{\infty} \frac{\left(C\langle n\rangle\right)^N}{N!} \cdot \mathrm{e}^{-C\langle n\rangle} \cdot \frac{\langle C\rangle^C \mathrm{e}^{-\langle C\rangle}}{C!} \tag{5}$$

with the same variance as in the case of NB type of $P(n)$ (cf. eq.(4) with $\langle C\rangle$ replacing k) [22].

Proceeding now to the most complex nuclear interactions one finds that they are dominated almost exclusively by the geometry of collision. The characteristic broad and flat shape of nuclear multiplicity distribution $P(N) = \sum_{\nu} p(\nu)P(N|\nu)$ emerges from the smooth behaviour of distribution of the number of participating nucleons ν, $\quad p(\nu) \sim b(\nu)\frac{db}{d\nu}$, over impact parameter b in a wide region of ν [24]. In general one has

$$\frac{D^2(N)}{\langle N\rangle^2} = \frac{D^2(\nu)}{\langle \nu\rangle^2} + \frac{1}{\langle \nu\rangle} \cdot \frac{D^2(n)}{\langle n\rangle^2} \tag{6}$$

(where n denotes multiplicity in hadronic collisions) with the first term being completely due to the nuclear geometry and dominating in the midle part of ν for minimum-bias events where $p(\nu) \sim$ const. In this region one gets multiplicity moments independent of the target mass and given by simple formula:

$$\mu_q = \frac{\langle \nu^q\rangle}{\langle \nu\rangle^q} = \frac{2^q}{q+1}. \tag{7}$$

This result holds for any situation where one has a number C of type $\mathbf{S}$ sources decaying independently into n_i particles each ($i = 1, \dots, C$). Namely, the normalized factorial moments F_q of the total distribution and those for each source $\mathbf{S}$, $F_q^{(S)}$, can be related to each other [25], for example:

$$F_2 = F_2^S + \frac{F_2^{(S)}}{\langle C\rangle} \tag{8}$$

with $F_2^S = \sum_C C(C-1)P(C)/\langle C\rangle^2$ being the normalized factorial moment of the distribution of $\mathbf{S}$'s and $\langle C\rangle$ their mean number whereas $F_2^{(S)} = \langle n(n-1)\rangle/\langle n\rangle^2$. Fig. 2 shows this quantity calculated as an average over 10^3 bins in the phase space as a function of the mean number of $\mathbf{S}$'s for different types of their distributions. Notice that F_2 is by definition the same for small $\langle C\rangle$ and that different types of fluctuations result in different dependence of F_2 on $\langle C\rangle$. Notice also that starting from the value $F_2 = 1.5$ for single source (corresponding, for example, to "elementary"

μp collisions for which $F_2 \simeq 1.5$ [26]) F_2 decreases very slowly for the flat $P(C)$ distribution tending to the plateau for moderately large number of S's and reaching value of $F_2 \simeq 1.3 - 1.35$ which coincides with that observed in heavy ion data [27]. In this way we can describe this two widely different (from the point of view of their compositeness) processes without necessity of questioning the independent collision picture in the later as has been advocated recently in [28].

4 Summary and conclusions

As we have just demonstrated our sources **S**'s fit nicely into description of all type of collisions. Let us return then back to discussion of the parameter λ as defined by eq.(1). We want to show now how it can serve as a measure of sources **S**'s (instead of being the measure of *chaoticity*, the notion of which does not appear here at all). Let us consider C sources **S**, each producing (on average) $\langle n\rangle$ like-sign bosons. We have

$$n^{(S)}_{pairs} = \frac{1}{2}\langle n(n-1)\rangle \tag{9}$$

pairs of such bosons from a single source and, respectively, $\langle C\rangle$ times this emerging from $\langle C\rangle$ sources:

$$n^{S}_{pairs} = \langle C\rangle n^{(S)}_{pairs} = \frac{1}{2}\langle C\rangle\langle n(n-1)\rangle \tag{10}$$

whereas the total number of pairs of like-sign bosons producing by $\langle C\rangle$ sources is instead equal to (cf. Appendix A)

$$N^{tot}_{pairs} = \frac{1}{2}\langle C(C-1)\rangle\langle n\rangle^2 + \frac{1}{2}\langle C\rangle\langle n(n-1)\rangle. \tag{11}$$

The λ parameter is, of course (cf. Appendix B), given by the ratio of both, which can be write as

$$\lambda = \frac{\mu_2(n)\langle n\rangle - 1}{\left[\mu_2(C)\langle C\rangle + \mu_2(n) - 1\right]\langle n\rangle - 1} = \frac{\mu_2(n)\langle N\rangle - \langle C\rangle}{\langle C\rangle\left[\mu_2(N)\langle N\rangle - 1\right]}, \tag{12}$$

where $\langle N\rangle = \langle C\rangle\langle n\rangle$ and $\mu_2(k) = \frac{\langle k^2\rangle}{\langle k\rangle^2}$, i.e., it is the second scaled moment for $k = n,\ N$ and C, respectively. Note that, as a consequence of our definition of EEC, $\lambda = 1$ for single source ($C = 1$) and decreases with the number of $\mathbf{S}$'s.

One can summarize now experimental situation as discussed previously in terms of our sources $\mathbf{S}$.

(i) In e^+e^- annihilations only $1 - 2$ sources $\mathbf{S}$ are produced [29]. This leads to large values of λ and increasing multiplicity comes mainly from the increasing number of secondaries from $\mathbf{S}$.

(ii) In pp collisions more sources are produced and multiplicity grows at first with the increasing number of sources and later, when this number saturates, because of increasing number of secondaries from $\mathbf{S}$, as in (i). This leads to λ decreasing with multiplicity, cf. Fig. 3. Note that the number of $\mathbf{S}$'s, $\langle C\rangle$ increases linearly with dN/dy (with $\sim 2 - 4$ charged pions per $\mathbf{S}$).

(iii) For nuclear collisions the number of the internucleonic collisions increases with the mass number of colliding nuclei what results in λ decreasing for heavier nuclei, cf. Fig. 4. (Also here the number of sources $\mathbf{S}$ deduced from λ increases linearly, this time with the number of participating nucleons, which is proportional to $A_{\mathrm{T}}^{1/3}$).

Finally, in Fig. 5 we show analysis of the p+Em collision events (provided by the IGM event generator [30]). Similarly looking experimental data were used in [31] to demonstrate the apparent increase of the 'coherence' when going in rapidity

from target towards projectile fragmentation regions. This conclusion was based on the increasing poissonianity of the respective multiplicity distributions in selected rapidity bins. However, in our case we are getting precisely the same pattern without invoking any notion of 'coherence' at all. It is enough that particles produced near the kinematic limits of reaction originate practically from one source only in which case in our approach they should be both poisson-like distributed and show $\lambda = 1$.

This last observation has some profound consequences which most probably can be tested in cosmic ray emulsion chambers experiments. Namely, if (based on the quantum-optical concepts) interpretation of [31] is correct, one should not observe any BEC effects in the fragmentation regions of reactions. However, as demonstrated in [32], the presence of such correlation (with their full strength, i.e., with $\lambda = 1$) would explain in a natural and consistent way many apparently 'strange' effects observed in the mentioned above cosmic ray experiments (which by definition measure almost exclusively the fragmentation region of hadronic collisions on air nuclei). In addition we would predict that, contrary to [31], λ will decrease towards the central region of reaction.

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Appendix A

We shall provide here an elementary derivation of eq.(12). Let $P_S(C)$ denote the number distribution of sources **S** and $p_1(n)$ the multiplicity distribution of like-sign particles from a single ($C = 1$) source. Because there are no BEC between particles emitted from different sources if their phases are random (which we assume here), therefore the total multiplicity distribution (again of like-sign particles) $P(N)$ is given by

$$P(N) = \sum_C P_S(C) \sum_{n_1+\cdots+n_C=N} \prod_{i=1}^{C} p_1(n_i). \tag{A1}$$

Using generating functions:

$$\begin{aligned} \pi(z) &= \sum_N P(N)\, z^N, \\ \pi_S(z) &= \sum_C P_S(C)\, z^C, \\ g(z) &= \sum_n p_1(n)\, z^n \end{aligned}$$

we have (with $u = g(z)$)

$$\begin{aligned} \pi(z) &= \sum_C P_S(C)\, \left[g(z)\right]^C = \pi_S\left[g(z)\right], \\ \pi'(z) &= \pi'_S(u)\, g'(z), \\ \pi''(z) &= \pi''_S(u)\, \left[g'(z)\right]^2 + \pi'_S(u)\, g''(z). \end{aligned}$$

Because, by definition,

$$\begin{aligned} \langle n \rangle &= g'(z)|_{z=1}, \\ \langle N(N-1) \rangle &= \pi''(z)|_{z=1}, \\ \langle C(C-1) \rangle &= \pi''_S(z)|_{z=1}, \\ \langle n(n-1) \rangle &= g''(z)|_{z=1}, \end{aligned}$$

then we get finally that

$$\langle N(N-1)\rangle = \langle C(C-1)\rangle\langle n\rangle^2 + \langle C\rangle\langle n(n-1)\rangle \tag{A2}$$

from which eq.(12) follows immediately.

Appendix B

We shall justify here the eq.(12) in more detail. Let us introduce (in one dimensional approximation) the usual (cf. refs. [6]-[10], especially [11]) two-particle *correlation factor*

$$W = 1 + \langle\cos(qr)\rangle \tag{B1}$$

where $q = p_1 - p_2$ (cf. eq.(1)) and $\langle\cos(qr)\rangle$ has symbolic meaning only and can be replaced by any other suitable expression (like $\langle\exp(-qr)\rangle$) without changing the outcome of our discussion. The essential point in our approach consists now in the observation that for n^S_{pairs} of like-sign bosons from **S**-type sources we have such correlation factor W whereas for the remaining $n^b_{pairs} = N^{tot}_{pairs} - n^S_{pairs}$ (cf. eqs.(10,11)) it does not appear (i.e., the corresponding pairs do not correlate among themselves). On the other hand, the *correlation function* for N particles

$$C_2 = 1 + \lambda\langle\cos(qr)\rangle \tag{B2}$$

which already contains parameter λ as defined in eq.(1) can be expressed in the following form,

$$C_2 = \frac{n^b_{pairs} + n^S_{pairs}\cdot W}{n^b_{pairs} + n^S_{pairs}} = 1 + \frac{n^S_{pairs}}{N^{tot}_{pairs}}\cdot\langle\cos(qr)\rangle, \tag{B3}$$

which immediately provides λ in terms of the ratio of pairs of like-sign bosons leading therefore to eq.(12).

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energies above that of ISR. Another example of such superposition is $P(n|\sqrt{s}) = \int_0^1 dK\chi(K)P(n|W(K))$ where $P(n|W(K))$ is the multiparticle distribution of the type discussed above for e^+e^- but corresponding only to the part of the total energy of the reaction given by $W(K) = K \cdot \sqrt{s}$ with K denoting inelasticity of the reaction under consideration [23]. It is widely known that Poissonian $P(n|W)$ with $< n(W) >$ being random variable obeying gamma distribution (e.g., because inelasticity fluctuations described by the inelasticity distribution $\chi(K)$) leads again to the NB type of multiplicity distribution (with k being parameter of gamma distribution this time [19]).

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Figure Captions

Fig. 1 Comparison of: (a) - shapes of multiplicity distributions $\psi(z=\frac{N}{\langle N\rangle})=\langle N\rangle P(N)$ and (b) - the energy dependence of the ratio of the dispersion to the average multiplicity, $\frac{D}{\langle N\rangle}$, for e^+e^- [3], pp [4] and AA [5] data.

Fig. 2 Second normalized factorial moment F_2 for 10^3 bins as function of number $\langle C\rangle$ of sources **S** for different types of their distribution.

Fig. 3 (a) - Parameter λ (as given by eq.(1)) as function of multiplicity per unit rapidity, dN/dy; (b) - the same with λ replaced by the mean number of sources **S**, $\langle C\rangle$ obtained from eq.(12). Data are from [16].

Fig. 4 (a) - Parameter λ (cf. eq. (1)) as function of the atomic number of target nucleus, A_T, for O+C, O+Cu, O+Ag and O+Au collisions at 200 GeV/nucleon (in target fragmentation region); (b) - the same with λ replaced by the mean number of sources **S**, $\langle C\rangle$ from eq.(12). Data are from [15, 18].

Fig. 5 Multiplicity distributions (for p+Em at $\sqrt{s}=20$ GeV) for rapidity windows covering different quarters of the kinematically accepted range $-3<y<3$ compared with Poisson distributions with the same value of $\langle N_{ch}\rangle$.

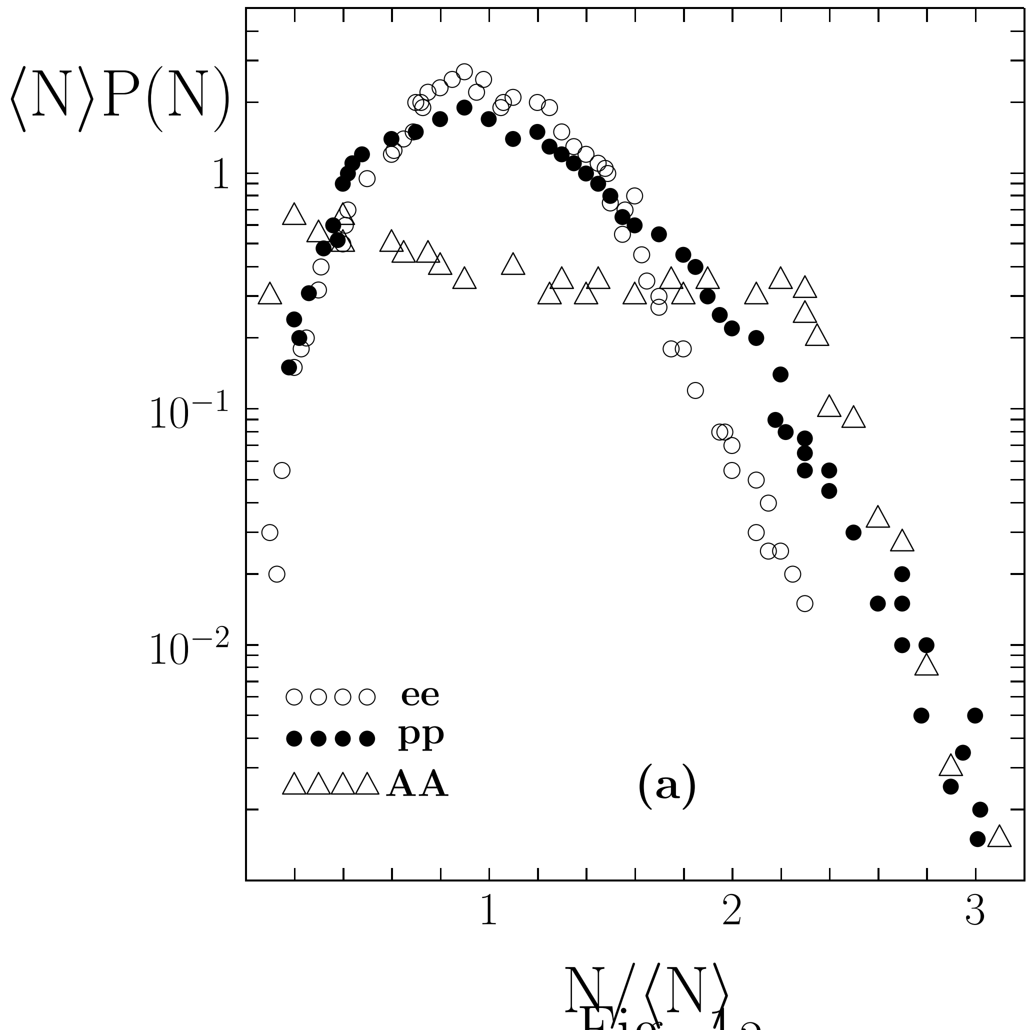

Fig. 1a

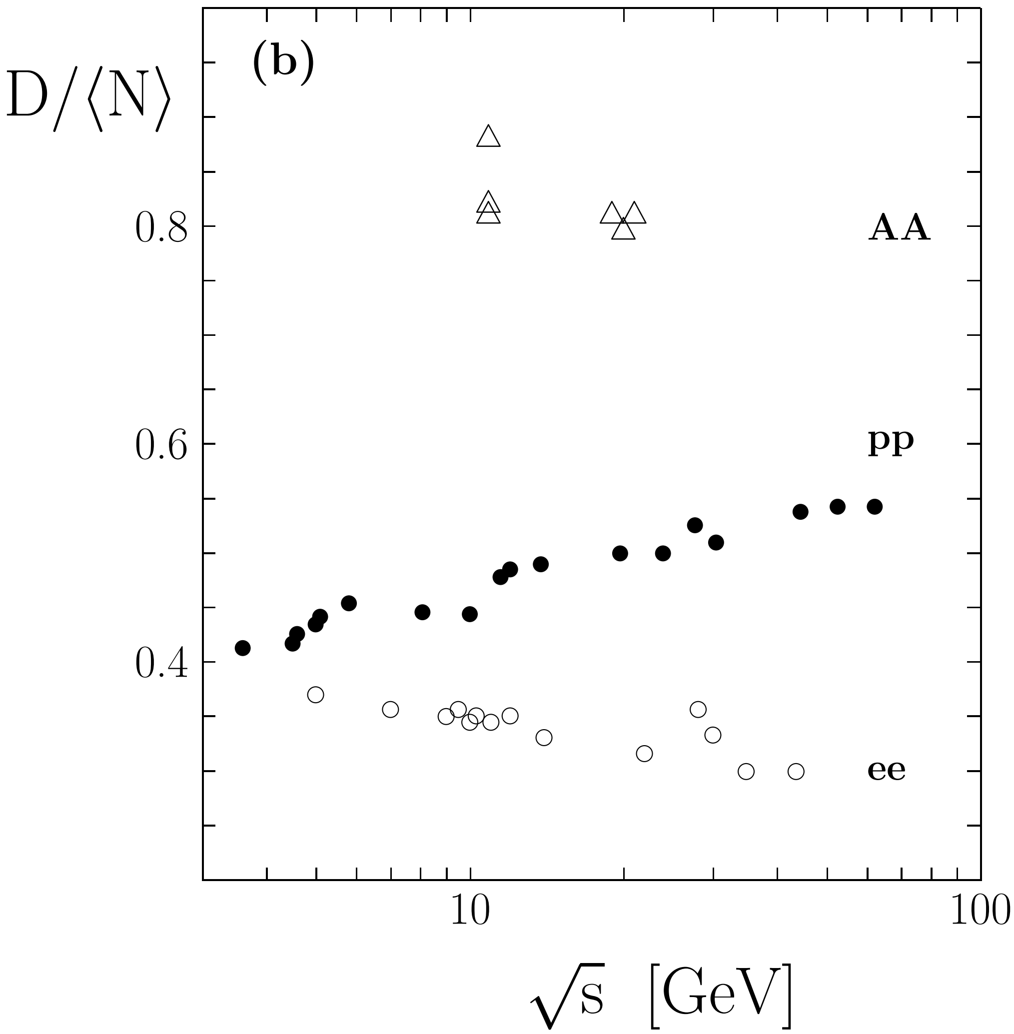

Fig. 1b

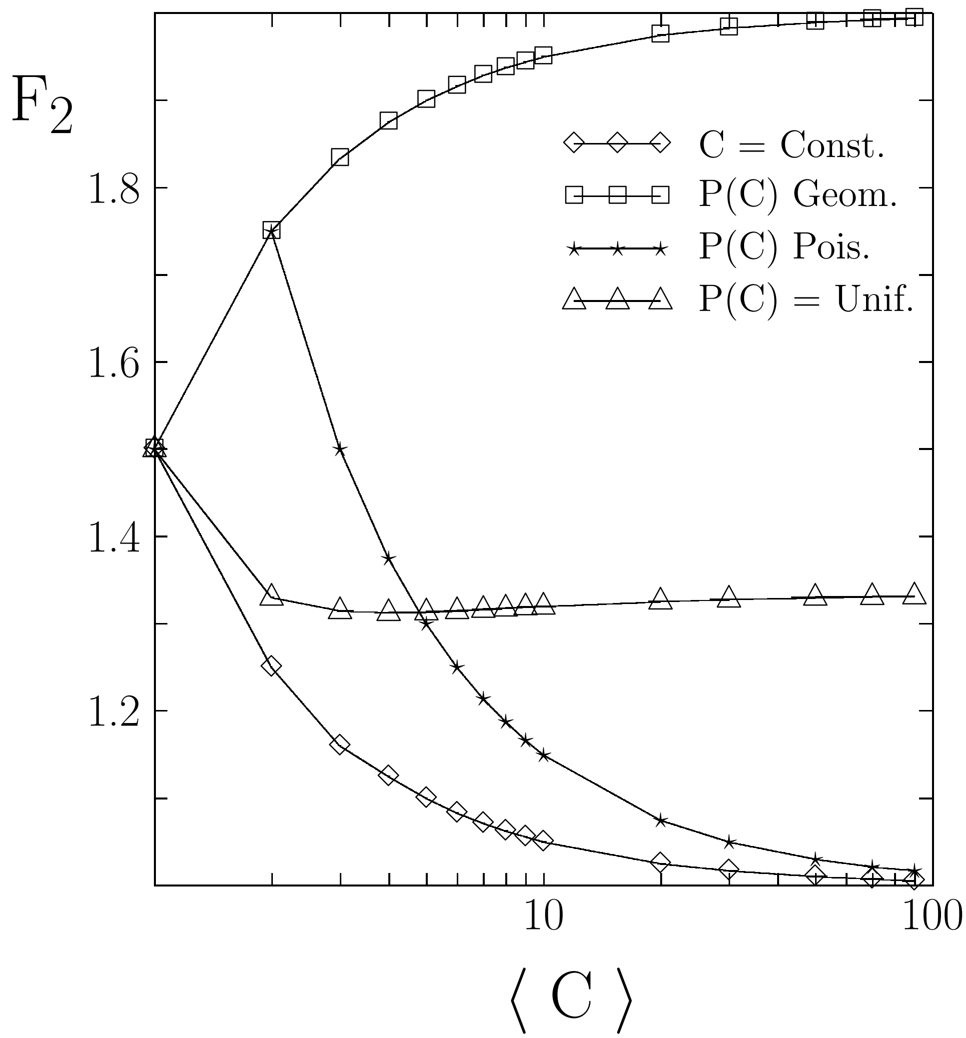

Fig. 2

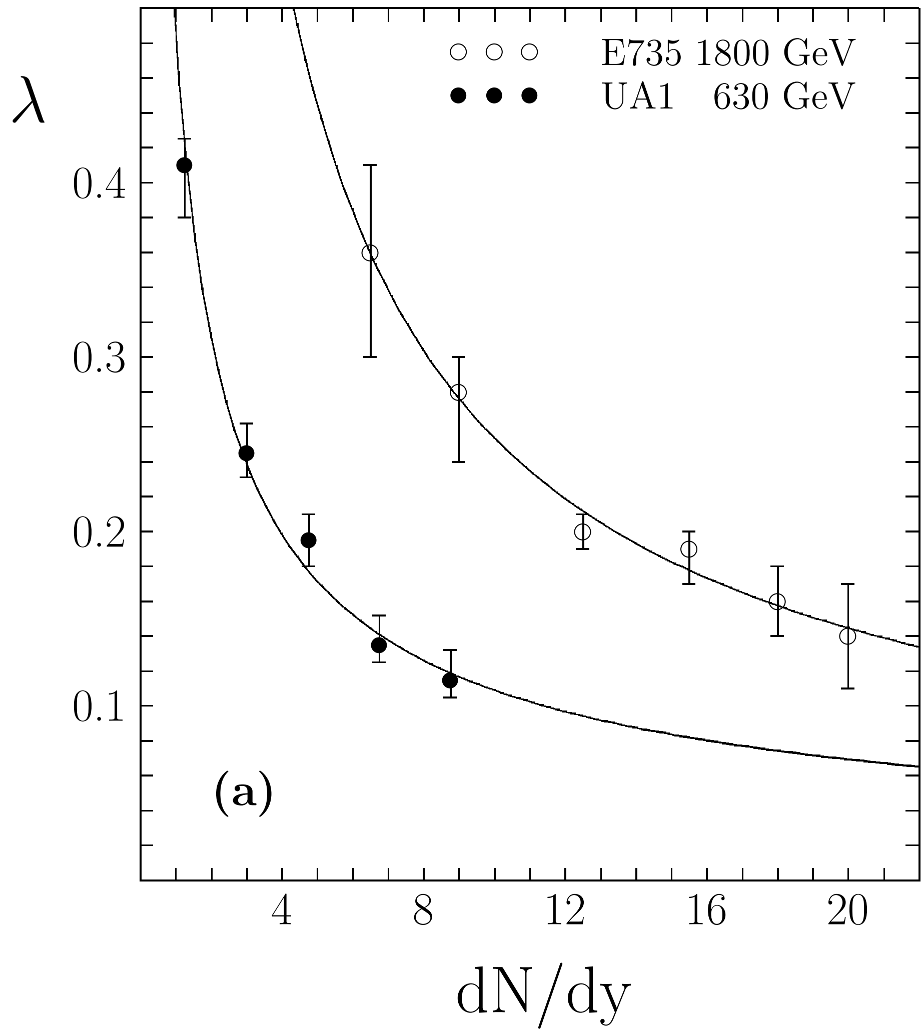

Fig. 3a

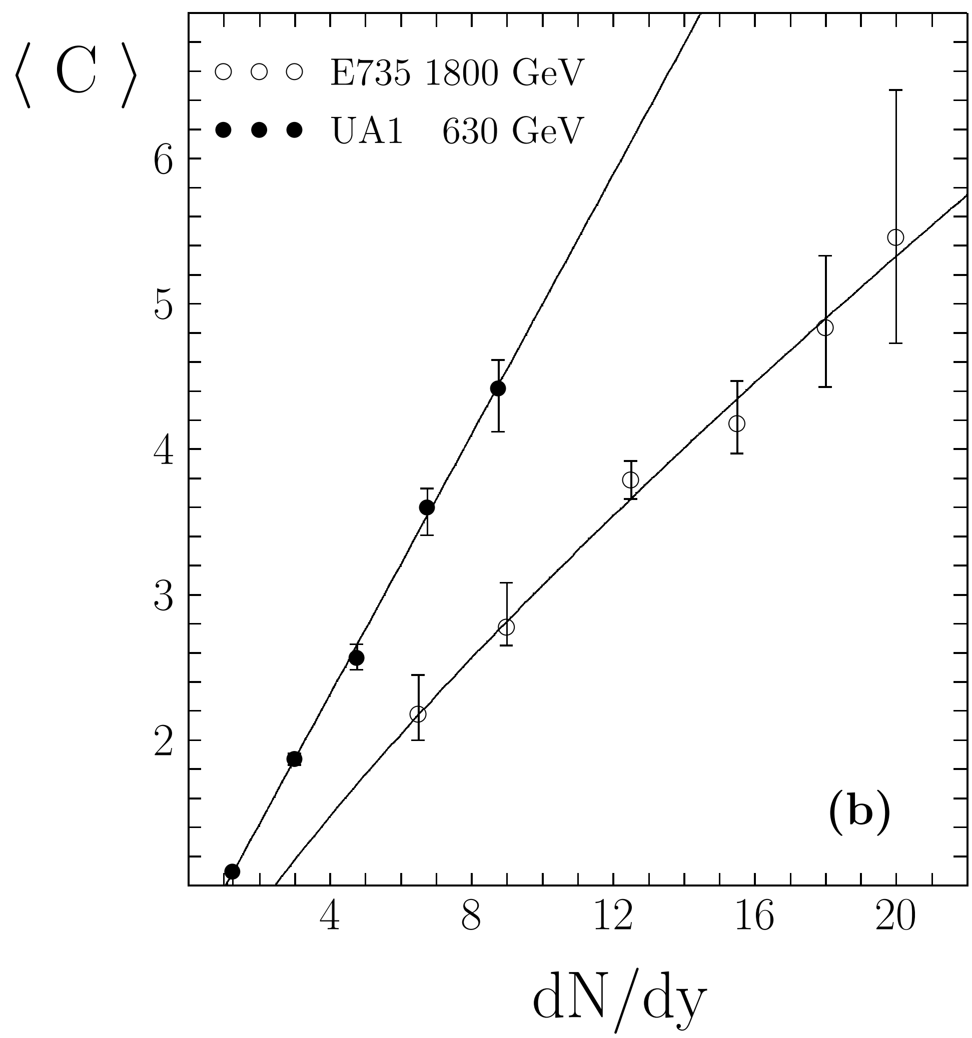

Fig. 3b

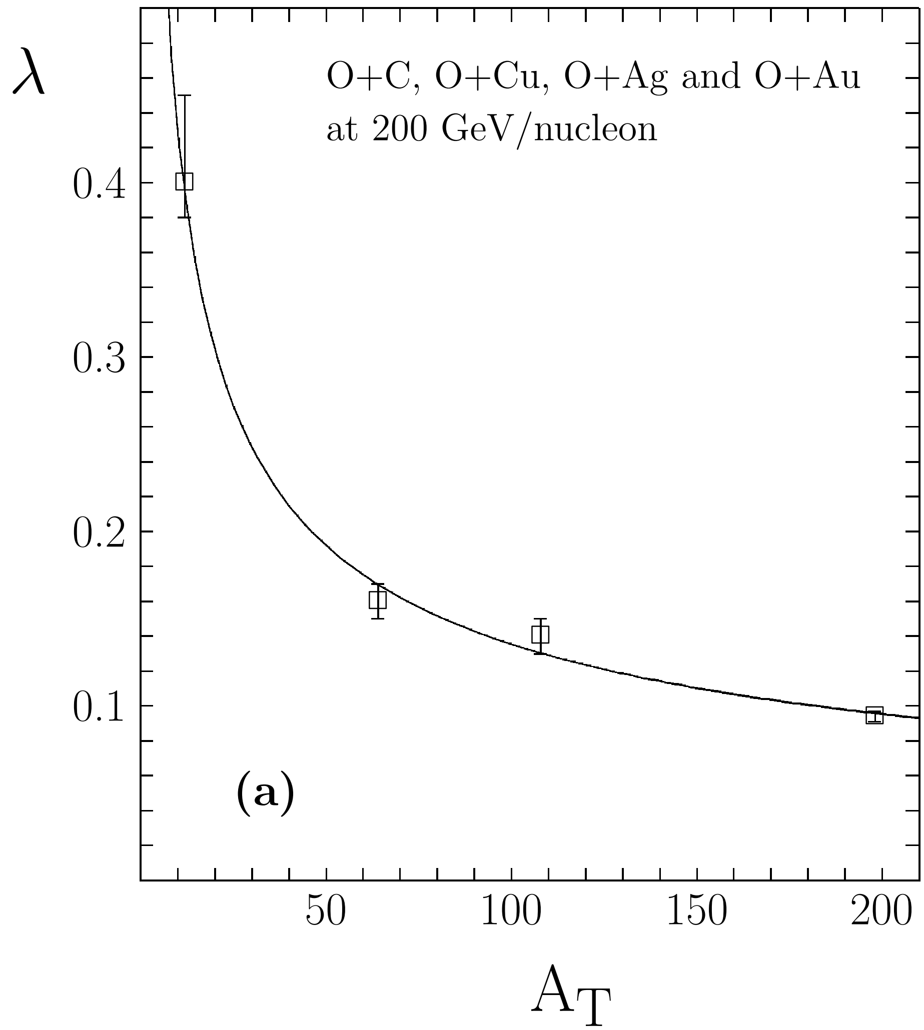
λ
O+C, O+Cu, O+Ag and O+Au
at 200 GeV/nucleon
0.4
0.3
0.2
0.1
(a)
50
100
150
200
A_T

Fig. 4a

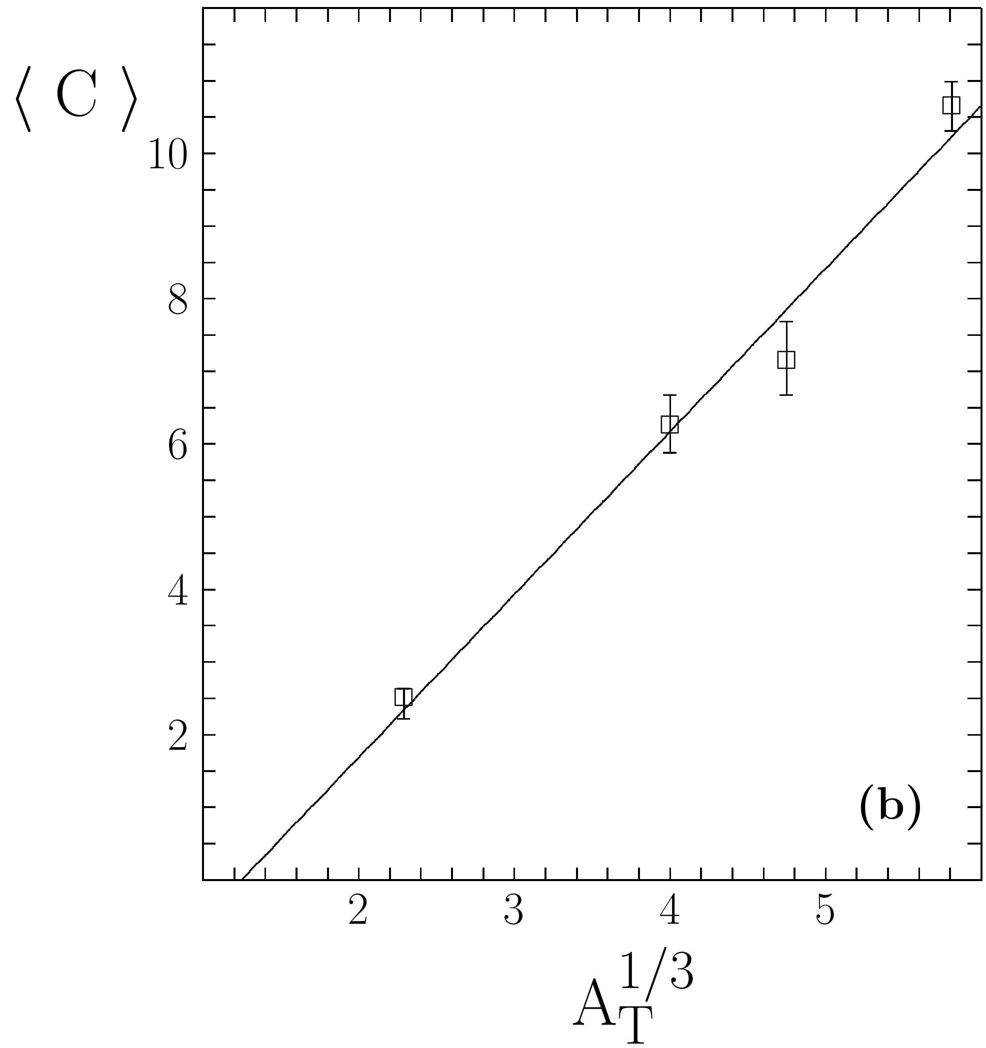

Fig. 4b

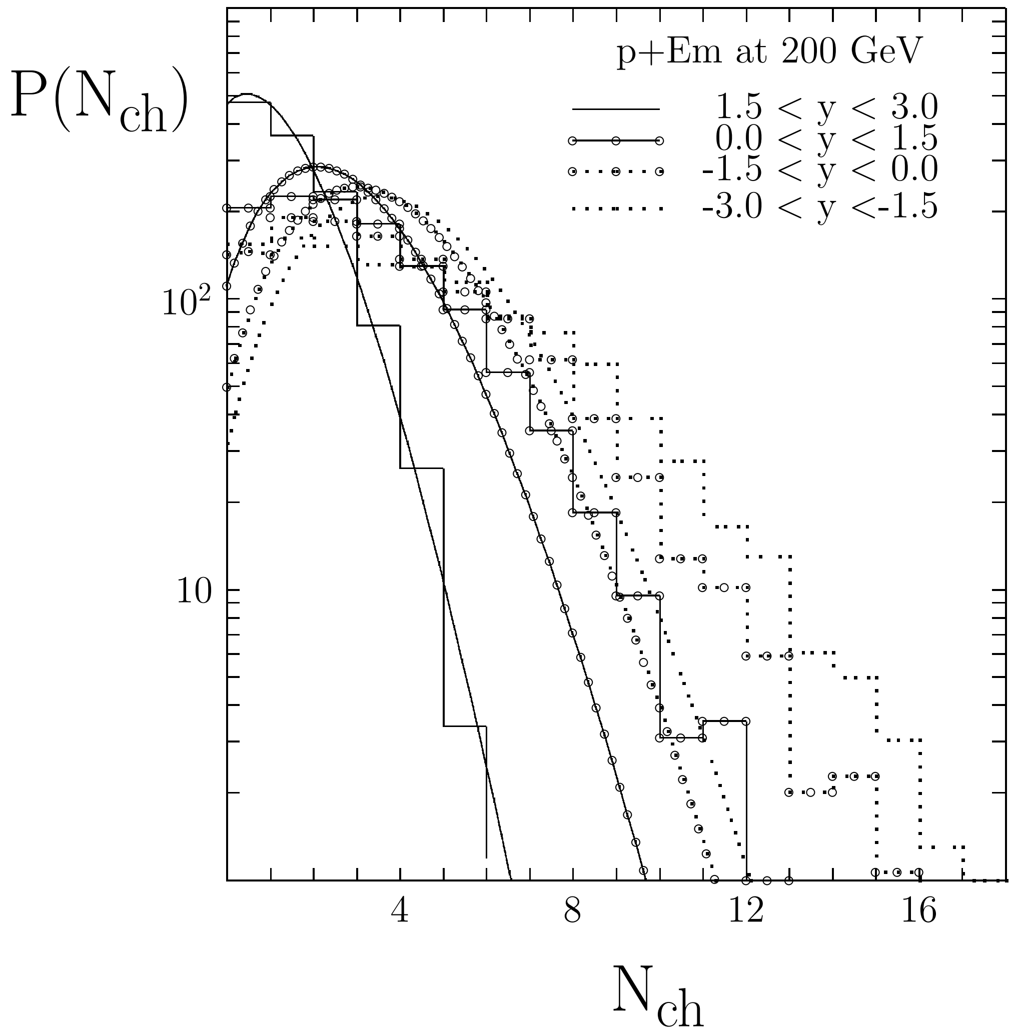

Fig. 5